IAC-06- D1.3.9

A METHOD FOR ALLOCATING RELIABILITY AND COST IN A LUNAR EXPLORATION ARCHITECTURE

David Young
Georgia Institute of Technology, Atlanta, GA, US
David.Young@gatech.edu

Dr. Alan Wilhite
Georgia Institute of Technology, Atlanta, GA, US
Wilhite@nianet.org

ABSTRACT

In January 2005, President Bush announced the Vision for Space Exploration. This vision involved a progressive expansion of human capabilities beyond Low Earth Orbit. Current design processes utilized to meet this vision employ performance based optimization schemes to determine the ideal solution. In these design processes the important aspects such as cost and reliability are currently calculated as an afterthought to the traditional performance metrics. The methodology implemented in this paper focuses on bringing these decisive variables to the forefront of the design process. To achieve this focus on cost and reliability in a lunar architecture design, a resource allocation technique from the business world will be implemented. This allocation technique optimally distributes the company's resources even though the actual performances of the products are uncertain. This method of resource allocation will be applied to a lunar architecture design to achieve the highest architecture reliability for a given budget. Once the methodology is created it will be implemented in a lunar architecture design tool. This tool will allow the decision maker to independently address the sensitivities of the lunar architecture's reliability to the overall budget of the program.

NOMENCLATURE

ATLAS	Advanced Technology and Lifecycle AnalysiS
CER	Cost Estimating Relationships
DDT&E	Design, Development, Testing, and Evaluation
DSM	Design Structure Matrices
ESAS	Exploration Systems Architecture Study
ETO	Earth to Orbit
FTA	Fault Tree Analysis
GA	Genetic Algorithm
IPPD	Integrated Produce and Process Development
IPT	Integrated Product Team
I_{sp}	Specific Impulse
MER	Mass Estimating Relationship
MDO	Multidisciplinary Design Optimization
NPD	New Product Development
OEC	Overall Evaluation Criteria
ROSETTA	Reduced Order Simulation for Evaluating Technologies and Transportation Architecture

RSE	Response Surface Equation
RSM	Response Surface Methodology
SSDL	Space Systems Design Laboratory
STS	Space Transportation System

INTRODUCTION

The purpose of the research is to improve on the design practices currently employed by the aerospace community. Currently top level design discriminators such as cost and reliability are calculated as afterthoughts to the design process. Cost and reliability are then used as the decision maker's criteria to determine the ideal solution. The methodology implemented in this paper focuses on bringing these decisive variables to the forefront of the design process. Once reliability and cost are independent variables they can be manipulated to meet the design requirements set out by the customer. This process will directly address the top level requirements early in the design process before the architecture design is set.

To achieve this methodology of making cost and reliability independent variables in the architecture design, a resource allocation technique from the business world will be implemented. Typically in the business world a company will have many competing products that will vie for a limited number of resources. Theories exist on how to appropriately distribute the company's resources even though the actual performances of the products are uncertain. This problem is very similar to the cost and reliabilities of different components of a lunar architecture design. There is a set amount of resources (total architecture costs and reliabilities) that must be allocated to the different vehicles that make up the lunar architectures. Once the methodology is created, the method will be implemented in a lunar architecture design tool. This computational tool will allow the decision maker to independently change cost and reliability goals and see the lunar architecture design change dynamically.

This lunar architecture design tool will be especially useful when combined with the Integrated Product and Process Development process. The IPPD process's goal is to make decisions with the most knowledge possible. This is typically accomplished through the use of Integrated Product Teams to get the opinions the many disciplines involved in the design process. The proposed methodology will further expand on this idea by providing the decision makers with information about how the budget of the project affects the design choices and the reliability of the system. This methodology will effectively bring the top level decision makers into the IPTs and demonstrate how changing programmatic parameters such as budget affect the vehicle design in real time.

This paper begins with an in-depth look into the motivation behind including investment as an independent variable in the design project. This includes a historical look at past NASA projects such as Apollo, the Space Transportation System, and the Exploration, Systems, Architecture Study. Problems with the current design problem are then addressed and a proposal for the solution of applying investment as an independent variable is presented.

MOTIVATION

The focus of NASA's design philosophies has changed significantly since its inception in the 1958. Early on in NASA's history the agency's design philosophy was focused on the performance aspects associated with space flight. The Apollo program is an example of this performance based design philosophy.

The Apollo program, and its predecessors Mercury and Gemini, were motivated by international competition between the Soviet Union and the United States. This motivation resulted in a successful lunar program that met the requirements to land on the moon, but failed to provide a sustainable architecture. After the success of Apollo 11, the next six Apollo missions, five lunar landings, were based on the motivation of scientific research and the desire to gain a better understanding of the origin of Earth. Unfortunately this goal was not nearly as captivating as that of international competition; and the cost, $2.5 Billion FY72, was prohibitive [1]. The political and social environment of the 1970s deemed the Apollo program as unsustainable and therefore was terminated with the last lunar mission of Apollo 17 in 1972. The resulting Apollo program cost over $25.4 billion, with only the building of the Panama Canal rivaling the Apollo program's size as the largest non-military technological endeavor ever undertaken by the United States [2].

NASA's next major design initiative was the Space Transportation System (STS). After the unsustainable Apollo program, there was a paradigm shift in the criteria used to select vehicles. Spacecraft were no longer being selected based upon the typical performance discriminators, but now cost and reliability were of increased importance to the customer. As the NASA budget began to shrink in the post-Apollo era the use of cost as a discriminator has become a priority. The STS program had undergone significant redesigns to try and reduce the cost of the system. There are many examples of less than optimum performance choices being made to decrease costs of the STS system. These include the use of aluminum instead of the more durable titanium for the orbiter, an expendable external tank instead of a reusable tank, and the use of solid rocket boosters instead of higher performance liquid boosters. Each of these cost cutting measures was made to try and make the shuttle more sustainable.

Even though cost was an important factor in the design of the STS program, the actual design methodology used was still performance focused. Cost was evaluated after each concept was defined. This resulted in multiple costly redesigns of the STS concept. Even after the cost cutting measures described above were implemented there were till at least five redesigns of the STS to try and produce a reliable system (Table 1).

CASE	1	2	2A	3	4
Payload bay (ft.)	10x30	12x40	14x45	14x50	15x60
Payload (klbs)	30	30	45	65	65
DDTE ($B)	4.7	4.9	5	5.2	5.5
Ops Cost ($M/flt)	6.6	7	7.5	7.6	7.7
$/Lb	220	223	167	115	118

Table 1: STS Configuration Redesigns [3].

This table enumerates the design problems faced during the shuttle design process. As the requirements changed, the design process had to be completely rerun manually with performance as the main design variables. Cost was only evaluated as an afterthought and then used as a discriminator between the designs. This flawed design process resulting in a vehicle which has never reached its cost or reliability goals. As a result the Space Shuttle cost over $33 billion dollars to become operational with an average cost of $1.3 Billion per flight [4].

In January 2004, President George W. Bush announced a new direction for NASA after the STS program. In his address to the public, the president announced a new Vision for Space Exploration in which NASA would return humans to the Moon by 2020. During the summer of 2005 the Exploration Systems Architecture Study (ESAS) team was assembled at NASA headquarters to conduct the design process to create the new lunar architecture to accomplish the Vision for Space Exploration. The team was assembled from 20 core team members from various NASA field centers with over 400 additional staff members assisting the design of the architecture.

The design process used to create the ESAS architecture is improved over that used by both the Apollo and STS engineers. As a result of the Space Shuttle accidents of the previous decade, the ESAS team had also included reliability to its list of core design criteria. The ESAS program was now considering performance, cost, and reliability in the design the new lunar architecture. Unfortunately, the ESAS team went about defining the architecture by using the traditional design process of determining performance characteristics and then defining costs for each of the contending architecture elements. The optimal vehicle elements were then chosen based upon performance, cost, and reliability. In fact the ESAS report claims nine advantages/features of the selected architecture. All nine of the advantages have to do with cost, affordability, or reliability/safety [5].

Unfortunately this methodology of comparing the costs and reliabilities of elements after the design process is both inefficient and slow. A further problem occurs when the requirements of the project change. In the months preceding this paper, changing cost caps and performance constraints have caused a massive redesign of the ESAS architecture. This is causing delays in the selection of the architectures since the design process must be repeated with the new performance criteria and constraints. To date, the NASA ESAS team is still working on the redesign of the next lunar architecture.

RESEARCH OBJECTIVES

Failures with previous design processes to adequately address cost and reliability early on in the design process has caused delays and costly redesigns in all previous NASA programs. The main objective of this research is to create a methodology to treat investment as an independent variable in the design process with respect to reliability. This will allow the top level customer requirements such as budget and required reliability to be directly addressed by the vehicle designers. Also, if cost is included as an independent variable in a design process it can be easily traded. This will allow the decision makers to adequately understand the reliability impacts of changing budgets. This method will allow the maximum reliability of a system to be achieved for a given design budget.

To accomplish this objective the reliability of different classes of vehicles must be calculated as a function of the development cost. This will include the increased reliability resulting from;

1. Changing vehicle types to change the inherent reliability of the system
2. Increasing the inherent component reliabilities of the subsystems
3. Adding redundancy to an existing design
4. Increasing the testing of a system (ground and flight tests)

These curves will be created for different classes of vehicles. The process of creating these models is similar to the Reduced Order Simulation for Evaluating Technologies and Transportation Architecture (ROSETTA) model utilized by both the Space System Design Laboratory at the Georgia Institute of Technology [6], as well as the Advanced Technology and Lifecycle AnalysiS (ATLAS) tool created at NASA Marshall [7]. Once these curves are obtained an algorithm will be created based upon the resource allocation research conducted by Kavadias, et.al [8]. The resulting algorithm will switch between different vehicle designs based upon the vehicle budget. This will allow the vehicle designers to see how the reliability of a vehicle increases with increasing budget. It will also allow the designer to determine a budget necessary to achieve a certain required reliability.

This design method will allocate the budget to the different elements of the architecture to produce the most reliable system. This will build on the first objective by not only choosing vehicle elements of the architecture, but also setting the ideal budget of each segment so that the optimized

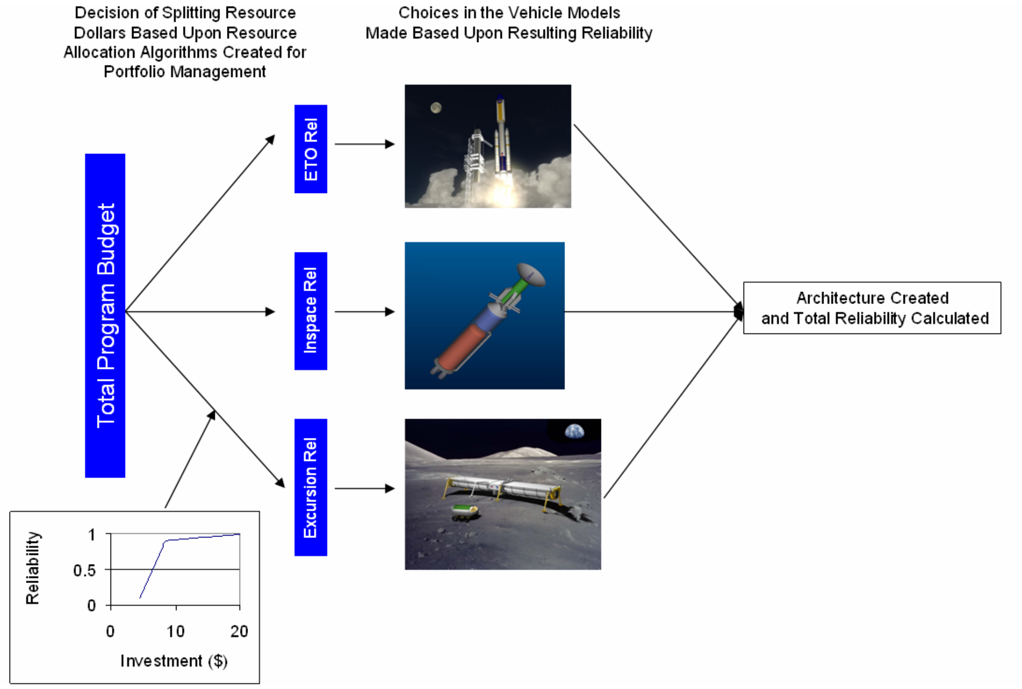

Figure 1: Proposed Methodology for Lunar Architecture Reliability Based Design

reliability of the system is achieved. This will allow the designer to change the budget of the entire mission and watch the elements of the architecture change so the most reliable system is achieved. A diagram of the proposed data flow is given as Figure 1.

This figure shows how the proposed technique will allocate the program budget to each of the segments of the lunar architecture based upon reliability vs. investment curves. The proposed algorithm will select the appropriate vehicle as well as the proper budget for each vehicle to produce the most reliable lunar architecture.

CURRENT CONCEPTUAL VEHICLE DESIGN PROCESS

To treat cost as an independent variable with respect to reliability a significant change must be made in the design process used to create a lunar architecture. The current conceptual vehicle design process used at the Space Systems Design Laboratory at the Georgia Institute of Technology utilizes industry designed computational codes to evaluate a design. The conceptual design process involves a combination of multiple different design disciplines. The conceptual design process involves the combination of many different design disciplines. These disciplines are treated as individual contributing analyses to the entire vehicle design. Each of these contributing analyses is coupled, which makes a difficult design problem. This coupling requires iteration between the disciplines to close the vehicle design. A Design Structure Matrix (DSM) is used to visualize this process.

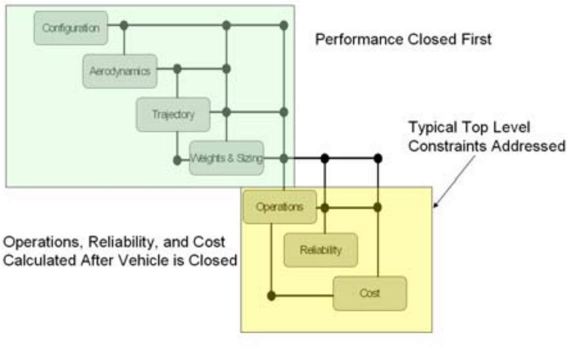

Figure 2: Typical Design Structure Matrix.

Once this analysis is defined there are many different methods to optimize the design. These are all grouped under the topic of Multidisciplinary Design Optimization (MDO). For very complicated designs, an MDO process, which directly runs the contributing analyses, may not provide the necessary efficiency. In these cases, a Response Surface Methodology (RSM) can be used to approximate the design disciplines. Once the MDO process has been completed, closing a particular design, a ROSETTA model can be made.

A Reduced Order Simulation for Evaluating Technologies and Transportation Architecture (ROSETTA) model is a parametric design tool utilized by the Space System Design Laboratory at the Georgia Institute of Technology to quickly evaluate how changing the design variable affects a vehicle. A ROSETTA model is a spreadsheet model that uses RSM to approximate each of the design disciplines.

METHODOLOGY

Ideally addressing cost as an independent variable with respect to reliability can be done with little changes to the traditional design process. This is desired since the traditional design tools utilized in the design process have all been tested and validated. Therefore the method presented in this paper will use response surface equations of the traditional design tools to evaluate the design disciplines. These disciplines will then be combined in a typical ROSETTA model to quickly evaluate the design.

ROSETTA models can affectively address the performance and cost aspects of a vehicle design, but the reliability calculations have traditionally been calculated separately. To address the reliability aspects of a vehicle design a dynamically changing fault tree will be included into the ROSETTA models. A Fault Tree Analysis (FTA) is a top-down or deductive approach to reliability modeling. This approach involves identifying the top level failure and uses an approach to identify potential causes for a system failure. Traditionally, FTA is conducted on a system once all of the elements for a vehicle are designed. For the methodology proposed in this paper a dynamically changing FTA will be included in the ROSETTA model. This FTA will include the effects of the changing component reliabilities, changing component and system redundancies, changing testing regiments, as well as changing vehicle configuration. This dynamically changing fault tree will then be used to calculate the reliability of a vehicle in real time as a part of the ROSETTA model.

Traditional Methodology

Once the dynamic reliability model is included in the ROSETTA model a traditional MDO approach of calculating the ideal system reliability for a given budget can be calculated. The problem is set up is shown as Figure 3.

As this figure shows the total architecture reliability budget would be split between the three segments of the lunar architecture (ETO, In-space, excursion). In each segment the budget would then be split again into the three methods of increasing reliability (component reliability, redundancy, and testing). These budgets will then be translated into resulting increases in reliability through reliability vs. investment curves derived from the individual subsystem elements. These curves will then be combined into the FTA to produce the overall reliability of the system. The ROSETTA model will also calculate the performance and costs not associated with increasing reliability through the traditional design process. Once an overall cost and reliability are calculated an Overall Evaluation Criteria (OEC) will be used to calculate the balance between cost and reliability dictated by the decision maker. This OEC will then be optimized by a Genetic Algorithm to produce the best OEC based upon a reliability investment. A Genetic Algorithm (GA) is necessary since there are both discrete and continuous variables in the design process.

This process is both cumbersome and difficult to implement. With 10 components for each vehicle and two vehicles for each segment there are over 183 variables associated with the reliability of the system. This will be a very difficult problem for the GA to solve and it gets exponentially more difficult and time consuming as the number of vehicles under consideration increase.

This optimizer based problem also has implementation and utilization issues with the management of a company. Extensive research has been done in the operations management community which state that optimization based decision making is not useful to top level managers [9,10,11]. These references have compiled data which states that top level managers want a real time tool that they can understand. Optimization based models are almost never implemented because managers can't see the impact of their decisions in real time.

Proposed Methodology

The proposed methodology breaks into two parts. The first part involves the creation of the reliability vs. investment curves for each of the vehicle classes under consideration in the architecture model. The second part is the real time tool requested by

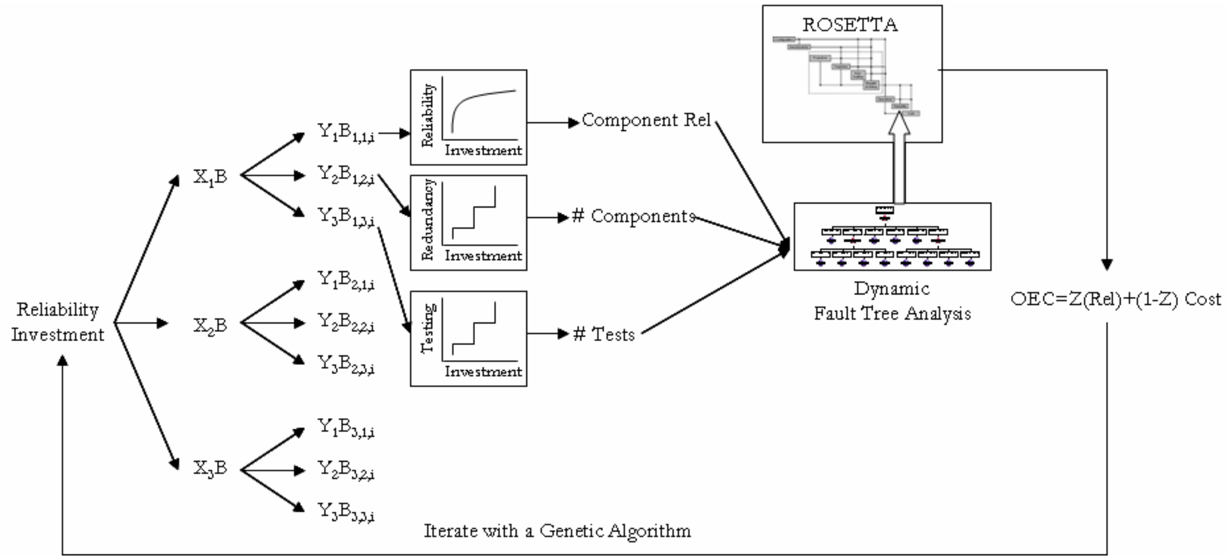

Figure 3: Traditional Optimizer Based Iterative Method

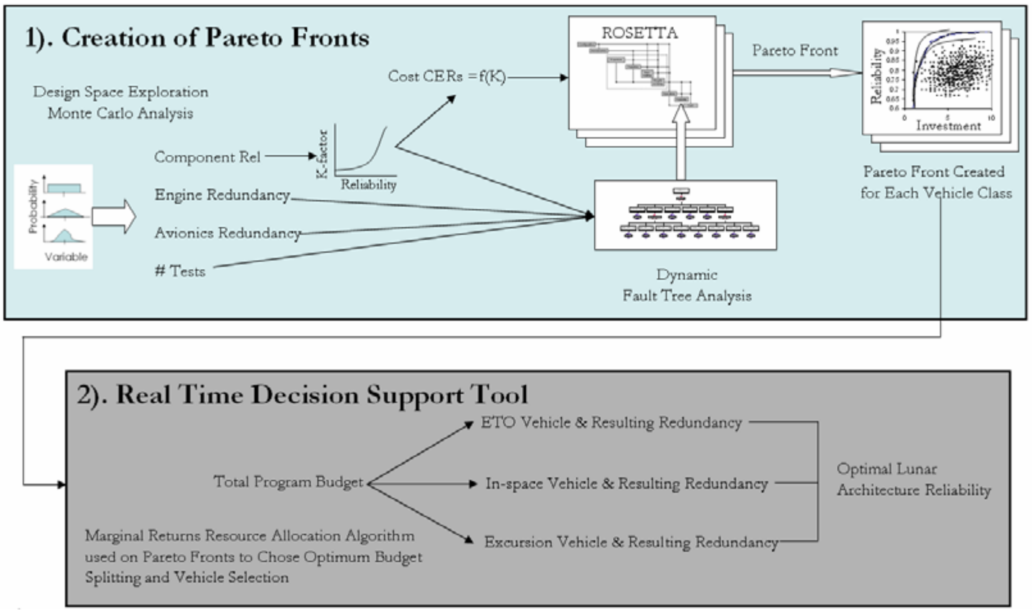

Figure 4: Proposed Two Part Methodology.

top level management to distribute the overall architecture budget to the competing segments to achieve the highest reliability for a given budget. This methodology is outlined in Figure 4.

The first part of this methodology involves the creation of reliability vs. investment Pareto Fronts. These Pareto plots are created by the use of a Monte Carlo analysis of the design space. For each of the variables under consideration (component reliability, redundancy, # tests, and vehicle design variables) a range of allowable values will be given. The Monte Carlo analysis will then randomly change the variables and the modified ROSETTA models will then design the vehicles and calculate the overall costs and reliabilities. These costs and reliabilities will then be stored and plotted on reliability vs. cost curve. After hundreds of thousands of runs the design space will be adequately explored and the Pareto frontier will be calculated as the ideal solutions for this ROSETTA model. These Pareto fronts will then be calculated for each ROSETTA model (vehicle) under consideration.

The second part of this methodology involves the creation of a real time decision support tool that will distribute the total program budget ideally to each of the vehicles to create an ideal (highest reliability) lunar architecture for the given budget. There are many ways to accomplish this distribution of resources. Traditionally optimizer based methods have been used, but because of the lack of implementation of these methods a marginal analysis approach will be investigated.

Marginal Returns Analysis

In operations management, there is field of research attempting to address the problem of selecting program portfolios for a new product development within a budget constraint. New Product Development (NPD) is problem faced by all companies. Companies must choose where to allocate scare resources to achieve the highest possible return on their investment.

Optimal portfolio determination of new projects is both a difficult and uncertain problem. The difficulty of selecting a portfolio is due to the uncertainty of the success of the projects as well as the combinatorial complexity of product combinations. Loch and Kavadias propose a solution to the resource allocation problem using marginal analysis [12]. The typical investment problem faced by companies is included as Figure 5.

As this figure demonstrates, a company usually has multiple product lines that share a limited resource pool. This resource pool must be divided optimally among the product lines to achieve the highest return on the resource investment. Companies will also face the decision of switching the products that are funded between periods based upon the different return vs. investment curves.

This is a difficult because the value vs. investment curves are either unknown or at best uncertain.

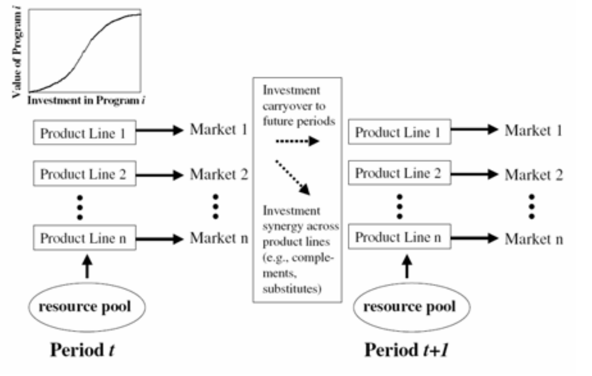

Figure 5: Typical Allocation Problem Faced by Companies [12].

The return functions of different products lines are uncertain, but these return functions generally fall under one of two classifications: increasing or decreasing returns. Increasing returns are applicable for product lines that are in the accelerating part of the return curves (Figure 5). These products generally are classified as new products that are gaining market share. As expected it is optimal to allocate all of the resources to a single project that has the highest return for investment. This was proved by mathematically by Loch [12] using Lagrange multipliers.

The second type of marginal returns is the class of decreasing returns. This type of return is most representative of mature product lines. The decreasing return is classified as a return where the derivative of the return with respect to the investment is still positive, yet the magnitude of the slope of the curve is decreasing or the second derivative is negative. In this case it is found that it is optimal in every period to split the budget among the product lines according to their marginal benefits. This is described in the following equations from Loch [12]:

$$\frac{f_{12}^{'}(\mu_1 c_{10} + c_{11})}{f_{22}^{'}(\mu_2(B_0 - c_{10}) + B_1 - c_{11})} = \frac{E[\Pi_{22}]}{E[\Pi_{11}]}$$

$$f_{11}^{'}(c_{10})E[\Pi_{11}] - f_{21}^{'}(B_0 - c_{10})E[\Pi_{21}] + \beta(\mu_1 - \mu_2) * f_{12}^{'}(\mu_1 c_{10} + c_{11})E[\Pi_{12}] = 0$$

Where: C is the investment
B is the budget
μ is the carried over investment
E[Π] potential market payoff
f is the return function

These equations assume that the multiple projects return function cross. If this is not the case than the project with the highest marginal benefit is chosen. This process can be used to provide a closed solution for the investment problem with multiple projects and a set budget.

For the lunar architecture selection problem the procedure of using marginal benefits to determine the ideal portfolio only needs to be calculated for one time period. This one period optimization also differs from the multi-period optimization in that there is a minimum budget necessary to keep a project active, as well as a maximum budget in which funding in excess of this maximum no longer produces returns. These maximum and minimum budgets (c_{up} and c_{down} respectively) are constraints to the optimization problem. A further simplification of this procedure can be accomplished by drawing a line from the investment minimum to the origin. This simplification doesn't affect the optimization algorithm because a program might as well invest the minimum if it invests at all because the return is linear. This procedure is demonstrated in Figure 6.

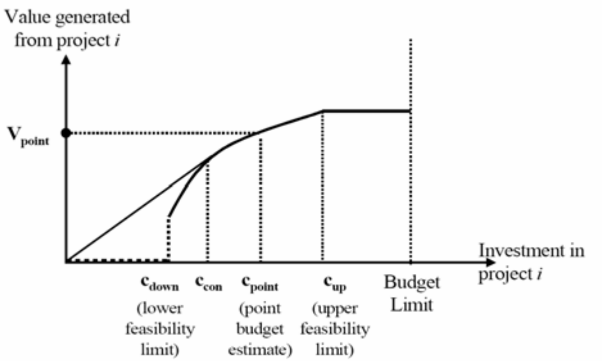

Figure 6: Investment Profile Example for Diminishing Returns [13].

The procedure for solving this problem is to allocate the budget to the highest return project until another project with a higher return passes it. The algorithm will then add funding to the new project. Both projects will then be continued (and so on) until the budget is attained. This optimization problem is stated mathematically as:

$$V(N) = \max_{c_i, i=1 \ldots N} \{ \sum_i g_i(c_i) \}$$

Implementation of Marginal Returns

The first problem faced by the resource allocation dilemma is the selection of a preferred vehicle for a segment of the lunar mission. The Pareto plots for each of the vehicle classes will be plotted on one set of axes. This is shown in Figure 7.

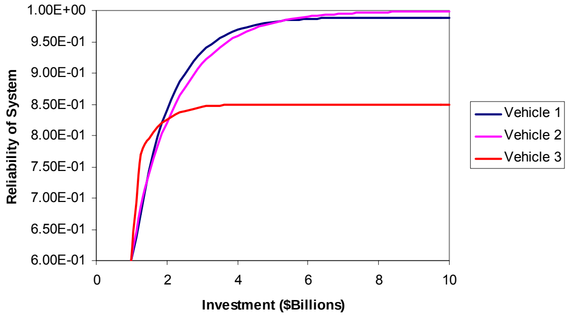

Figure 7: Nominal Vehicle Selection Problem Using Resource Allocation

For each investment point there is one ideal vehicle (vehicle that produces the highest reliability for the investment). Because only the ideal vehicle will be chosen for each segment the maximum of these Pareto plots will then be taken. for a minimum investment. This maximum will then be used in the resource allocation problem associated with dividing the budget to each of the segments.

In the case of the architecture selection there are three mission segments as described previously. Each of these mission segments has multiple vehicles that can solve the mission. These vehicles are pre-selected by the designer to be feasible for the mission. The maximum of the segment plots will then be used as the input to the architecture selection problem. This maximum and its fit are shown as Figure 8.

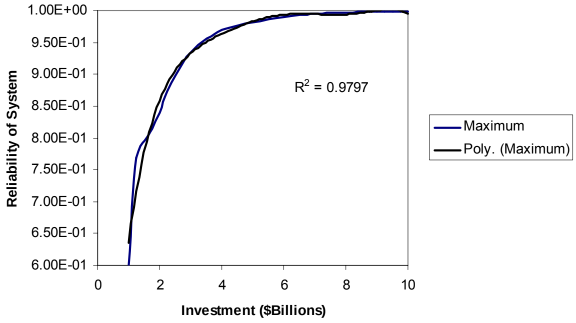

Figure 8: Maximum of ETO Segment Reliability with Curve Fit.

This maximum plot will then be combined with the maximum plots for the other segments. These plots will then be combined into a new product development problem with the budget of each segment being allowed to change to produce the most reliable system.

The total reliability of the system is given as the product of the reliabilities of each of the segments. The resource allocation problem treats the total benefit as the combination of the benefits of each of the products. To accomplish this transformation, the log of the reliabilities of each segment will be computed. This log transformation accomplishes two goals. It allows the log probabilities of each segment to be added, and the max log-probability will be taken. The second goal is that it smoothes out the maximum reliability curves to simplify the marginal analysis. The resource allocation algorithm can then directly compute the ideal resource allocation via the marginal returns analysis described in the previous section.

There are many advantages of the proposed methodology to traditional optimizer based methodology. The first advantage is that the decision making tool can adjust in real time to get the sensitivities of the system reliability to the overall budget. A second advantage to this method is that it evolves well to larger systems. This method is good for any number of vehicles as long as a Pareto front is created for each vehicle class. Another advantage is that there is no iteration or optimizer necessary. This greatly simplifies the problem and allows management to watch the vehicle configurations and resulting reliabilities change with the changing budgets. The one main disadvantage of this methodology is the lack of a true optimizer makes the solution dependant on the number of runs completed in the Monte Carlo analysis. This disadvantage can be mitigated as long as the engineer running the analysis runs enough simulations so that the design space is fully defined in the Monte Carlo.

CONCLUSION

The research proposed in this paper attempts to improve the aerospace design process to adequately address the reliability and costs associated with a lunar architecture. The traditional design process used in the conceptual design of past NASA projects (Apollo, STS, ESAS) does not address the cost and reliability early on in the design process. As a result, costly redesigns are necessary and the process gets delayed.

The method proposed treats the budget of a lunar architecture as an independent variable in the design process. As an independent variable the budget can be varied and the resulting sensitivities on reliability can be addressed. This methodology utilizes fast acting parametric models that use a response surface methodology to approximate the traditional disciplinary design tools. These parametric models can then be implemented to create a Pareto front of reliability vs. investment for each of the vehicle models. These Pareto fronts are then combined with a Marginal Returns analysis to create a real time decision support tool. This tool can be used by managers to select the ideal configurations of each of the architecture segments to produce the highest reliability for the given lunar architecture budget. The sensitivities of the reliability on the budget can also be shown by this real time tool.

ACKNOWLEDGEMENTS

The authors would like to thank the Advanced Technology and Life-cycle AnalysiS Tool (ATLAS) program at NASA Marshall SFC which funded the completion of some of the ROSETTA models needed for this research via a grant from the National Space Science and Technology Center. The authors would like to thank the members of the Space Systems Design Lab at the Georgia Institute of Technology.

REFERENCES

[1] Lewis, R. S., *The Voyages of Apollo: The Exploration of the Moon.* Quadrangle, New York, NY 1975.

[2] Project Apollo:: A Retrospective Analysis, Online. Internet 25 June 2006. Available: http://history.nasa.gov/Apollomon/Apollo.html

[3] Heppenheimer, T.A., *The Space Shuttle Decision 1965-1972.* Smithsonian Institute Press, Washington, D.C., 2002.

[4] David, L., Total Tally of Shuttle Fleet Cost Exceed Initial Estimates, Online. Internet. 25 June 2006. Available: http://www.space.com/news/shuttle_cost_050211.html

[5] Stanley, D., et. al. Exploration Systems Architecture Study Final Report, Summer 2006.

[6] Marcus, L., Olds, J. R., et. al., “Technology Assessment for Manned Mars Exploration Using a ROSETTA Model of a Bimodal Nuclear Thermal Rocket (BNTR),” AIAA Space 2001 Conference and Exposition, Albuquerque, NM, August 28-30, 2001.

[7] Thompson, R., O’Neil D., “System Architecture Modeling for Technology Portfolio Management using ATLAS,” IEEE Aerospace Conference, Big Sky, Montana, March 2006.

[8] Kavadias, S., Loch, C. *Project Selection Under Uncertanty: Dynamically Allocating Resources to Maximize Value,* Hillier International Series in Operation Research and Management Science, Kluwer Academic Publisher, 2003.

[9] Loch, C. H., M. T. Pich, C. Terwiesch and M. Urbschat: HSelecting R&D Projects at BMW: A Case Study of Adopting Mathematical Programming ModelsH, *IEEE Transactions on Engineering Management* 48 (1), 2001, 70 - 80.

[10] Schmidt, RL, JR Freeland. 1992. Recent progress in modeling R&D project-selection processes. IEEE Trans. Eng. Management 39(3) 239-246

[11] Beaujon, G. J., S. P. Marin., G. C. McDonald. 2001. Balancing and optimizing a portfolio of R&D projects. *Naval Logist. Quart.* 48(1) 18–40.

[12] Loch, C. H., Kavadias S. “Dynamic Portfolio Selection of NPD Programs Using Marginal Returns,” *Management Science*, Vol. 48 (10) pp. 1227-1241.

[13] Kavadias S., Loch, C. H., “Using Marginal Returns to allocate the R&D Budget at GemStone,” September2004.